Geomechanics and Engineering, *Vol. 9, No. 6 (2015) 757-774*
DOI: http://dx.doi.org/10.12989/gae.2015.9.6.757

Numerical modeling of uplift resistance of buried pipelines in sand, reinforced with geogrid and innovative grid-anchor system

Majid Mahdi [a] and Hooshang Katebi*

Department of Civil Engineering, Tabriz University, Tabriz, Iran

(*Received March 15, 2015, Revised October 20, 2015, Accepted October 28, 2015*)

Abstract. Reinforcing soils with the geosynthetics have been shown to be an effective method for improving the uplift capacity of granular soils. The pull-out resistance of the reinforcing elements is one of the most notable factors in increasing the uplift capacity. In this paper, a new reinforcing element including the elements (anchors) attached to the ordinary geogrid for increasing the pull-out resistance of the reinforcement, is used. Thus, the reinforcement consists of the geogrid and anchors with the cylindrical plastic elements attached to it, namely grid-anchors. A three-dimensional numerical study, employing the commercial finite difference software FLAC-3D, was performed to investigate the uplift capacity of the pipelines buried in sand reinforced with this system. The models were used to investigate the effect of the pipe diameter, burial depth, soil density, number of the reinforcement layers, width of the reinforcement layer, and the stiffness of geogrid and anchors on the uplift resistance of the sandy soils. The outcomes reveal that, due to a developed longer failure surface, inclusion of grid-anchor system in a soil deposit outstandingly increases the uplift capacity. Compared to the multilayer reinforcement, the single layer reinforcement was more effective in enhancing the uplift capacity. Moreover, the efficiency of the reinforcement layer inclusion for uplift resistance in loose sand is higher than dense sand. Besides, the efficiency of reinforcement layer inclusion for uplift resistance in lower embedment ratios is higher. In addition, by increasing the pipe diameter, the efficiency of the reinforcement layer inclusion will be lower. Results demonstrate that, for the pipes with an outer diameter of 50 mm, the grid-anchor system of reinforcing can increase the uplift capacity 2.18 times greater than that for an ordinary geogrid and 3.20 times greater than that for non-reinforced sand.

Keywords: numerical analysis; uplift resistance; buried pipelines; reinforced sand; grid-anchor; geogrid

1. Introduction

The use of buried pipelines in urban areas has experienced impressive growth during the last decades. This has happened mainly because the high demand for basic services has forced the expansion of the pipeline nets which transport gas, oil, communication and electrical cables amongst others. Failure of an oil or gas pipeline has serious economic and environmental

*Corresponding author, Associate Professor, E-mail: katebi@tabrizu.ac.ir
[a] Ph.D. Student, E-mail: m.mahdi@tabrizu.ac.ir

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

consequences. The main reasons for the use of buried pipelines for such services are the low installation costs, low environmental impact and protection of the facilities (Saboya *et al*. 2012).

The behavior of a buried pipeline is remarkably influenced by the interaction between the pipe and the surrounding ground as well as the backfill material. In designing a pipeline the efforts to increase the depth of cover to mitigate the traffic loading is countered by the increase in the lateral and vertical earth pressures as well as the buoyant forces. These contrary design objectives frequently result in compromises that increase the cost and maintenance concerns.

Increasing the depth of the vertical cover is imperative to reduce the concentrated traffic loads imposed on a pipeline; this results in high vertical loads. The resultant vertical loads require a costly high strength pipe section (Mohri *et al*. 2001).

It is possible to reduce the depth of coverage if the pipeline can gain additional resistance through the use of reinforced soil. This paper aims to investigate the enhancement effect of geogrid and grid-anchor incorporation on the uplift resistance of buried pipelines in loose and dense sand.

2. Background

Recently, in order to ascertain the uplift behavior of the buried pipelines and anchor plates as a function of the burial depth, type of the soil and degree of compaction, several studies have been carried out through analytical, numerical, and experimental modeling (Rowe and Davis 1982, Trautmann *et al*. 1985, Dikin 1994, Finch 1999, White *et al*. 2001, Bransby *et al*. 2002, Cheuk *et al*. 2005, White *et al*. 2008, Choobbasti *et al*. 2009, Lee 2010 and Niroumand and Kassim 2013, 2014a, b, c).

Thusyanthan *et al*. (2008) carried out a series of centrifuge model tests to investigate the upheaval buckling resistance of buried pipelines in cohesive soils. Pipe vertical displacement, excess pore pressure at the invert pipe and resistance of covering soil were measured. In this regard, significant parameters such as rock dump depth, pipe pullout rate, burial depth, and interval time between burial and commissioning has investigated. The tests results revealed that the burial depth has a good correlation with the uplift resistance. In addition, they concluded the effect of rock dump on uplift resistance, has a vital role rather than clay backfill for the rate of pullout in both slow and fast conditions.

An analytical study of pipeline upheaval buckling in clays has been conducted using the finite element analysis by Newson and Deljoui (2006). The results indicate that uplift factors are similar to those factors which found for plate anchors, regarding values approximately 4.5-6.5% greater for the pipelines.

A small-scale physical model test was done by Trautmann *et al*. (1985) to measure the maximum uplift force of buried pipelines in dry sand. The maximum uplift force of buried pipelines as a function of density of soil and pipe depth was considered. Under plane strain condition, the results demonstrated that the uplift resistance of loose sand is considerably low in compared with the uplift resistance of dense sands.

A series of centrifuge model tests were conducted by Huang *et al*. (2014) to study the uplifting behavior of shallow buried pipeline subjected to seismic vibration in liquefiable sites. The uplifting mechanism was discussed through the responses of the pore water pressure and earth pressure around the pipeline. Additionally, the analysis of force which pipeline was subjected to before and during vibrations was introduced and proved in order to be reasonable by the comparison of the measured and the calculated results. The uplifting behavior of pipe is the combination effects of multiple forces, and is remarkably depend on the excess pore pressure.

Selvadurai (1989) conducted experiments that utilized a pipe with a diameter of 150-mm and proposed a method that increased pipe uplift resistance by putting a geogrid over the upper part of the pipe. According to their conclusion, when the peak loads are considered, the incorporation of geogrid leads to a substantial increase in the uplift capacity of pipes.

Keskin (2015) established a series of three dimensional finite element analyses model and confirmed to be effective in capturing the behavior of plate anchor reinforced sand by comparing its predictions with experimental results. The results showed that the geogrid reinforcement had a considerable effect on the uplift capacity of horizontal square plate anchors in sand. The improvement in uplift capacity was found to be strongly dependent on the embedment depth and relative density of sand.

Zhu *et al*. (2014) introduced a new type of umbrella shaped anchor. The uplift behavior of this ground anchor in clay is studied through a series of laboratory and field uplift tests. The test results show that the umbrella-shaped anchor has higher uplift capacity than conventional anchors. The failure mode of the umbrella shaped anchor in a large embedment depth can be characterized by an arc failure surface and the dimension of the plastic zone depends on the anchor diameter. The anchor diameter and embedment depth have significant influence on the uplift behavior.

Faizi *et al*. (2014) and Jahed Armaghani *et al*. (2015) investigated the enhancement effect of the geogrid incorporation on the uplift resistance of the buried pipelines in loose sand. Hence, for verification purposes, an experimental program comprising 11 small-scale uplift tests, accompanied by the numerical analyses using PLAXIS 3D TUNNEL, was conducted. Their findings reflect the significance of applying geogrid to enhance the uplift resistance. It was found out when peak uplift resistance is of interest, the incorporation of two layers of geogrid does not have a significant effect on the uplift resistance. When the residual uplift resistance is of interest, however, employing two layers of geogrid compared to utilizing one layer of geogrid with a similar length is auspicious.

One of the geosynthetic's applications is in the construction of a reinforced soil foundation to increase the bearing capacity of shallow spread footings. Recently, in order to improve the bearing capacity of soil, a new reinforcement element has been introduced and numerically studied by Mosallanezhad *et al*. (2007, 2010) and Hataf *et al*. (2010). The main idea behind the new system is adding the so-called grid-anchors to ordinary geogrids. Fig. 1 shows a schematic arrangement of the system. With regard to Fig. 1, a foundation of width B that is supported by the soil reinforced with grid-anchor is shown; the anchors are made from 10×10×10 mm cubic elements. Results showed that the grid-anchor system of reinforcing can increase the bearing capacity 2.74 times greater than that for ordinary geogrid and 4.43 times greater than that for non-reinforced sand. Also, the results show that by using grid-anchor and increasing the number of layers of them in the same proportion, at the same cyclic load applied, the amounts of permanent settlements have been reduced and the numbers of cycles to reach have decreased.

This paper seeks to investigate the enhancement effect of the geogrid and grid-anchor incorporation on the uplift resistance of the buried pipelines in loose and dense sands, using the commercial finite difference software FLAC-3D. For enhancement of the uplift resistance of buried pipelines, the anchors must be installed below the geogrid. Fig. 2 exhibits a schematic arrangement of the system. In this system, the anchors are assumed to be consisted of a cylindrical plastic element with 3 cm in diameter and 1 cm in height as the anchor plate, attached to a geogrid net with a plastic cable of 8 cm in length.

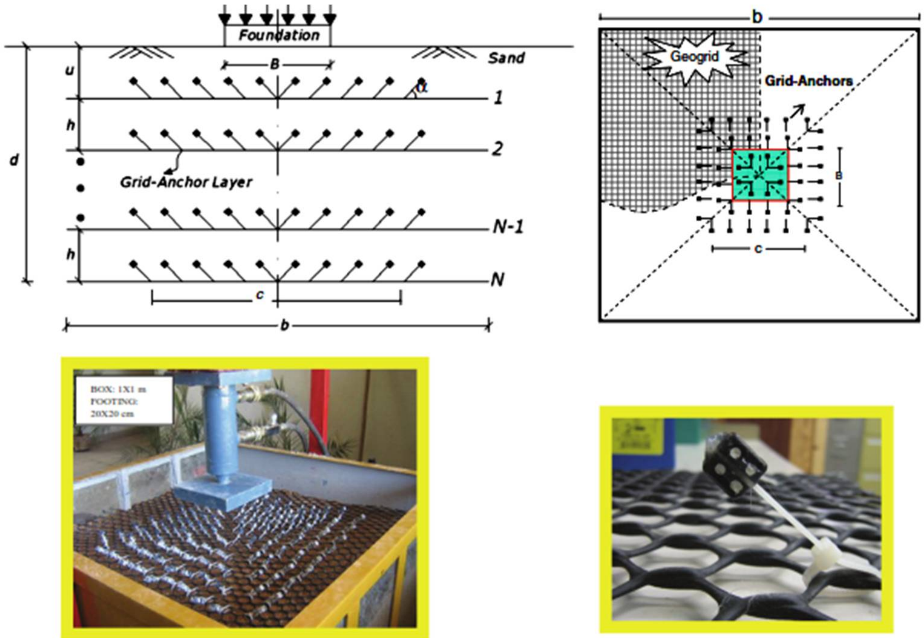


Fig. 1 Schematic model and photos of the square foundation on the grid-anchor reinforced soil (Hataf *et al*. 2010)

3. Numerical analysis

The finite difference program "FLAC-3D" (version 5.0) was used to model the uplift capacity of the pipelines buried in sand reinforced with the geogrid and grid-anchor systems. A 3D analysis was carried out to investigate the uplift behavior of the circular pipelines to identify the effects of the most important parameters including the pipe diameter, burial depth, soil density, number and width of the geogrid layers and stiffness of the reinforcement and anchors on the uplift resistance per unit length of the pipe at the sandy soils.

Soil behavior has been modeled by use of the Mohr-Coulomb constitutive model. The model was chosen for some rational reasons like its simplicity, easiness and higher community understanding of the model, i.e., simplicity refers a relatively simple model compared to advanced constitutive models such as Nor-Sand (NS) and Cam-Clay.

It is worthy to note that, the Mohr-Coulomb model only demands a few parameters that would be easily determined through direct shear tests, unlike other models that demand their parameters through proper controlled triaxial testing. Further, the Mohr-Coulomb model is widely popular in the community for modeling the behavior of soils because of its simplicity and need of popular soil characteristics such as friction and dilation of soils (Robert and Thusyanthan 2015).

Parameters used in the analysis are tabulated in Table 1. The soil parameters were extracted from experimental last studies by Faizi *et al*. (2014) and Hataf *et al*. (2010). Also the geogrid and anchor properties measured from materials which prepared by researchers for future experimental studies.

The geogrid layers are free in *x*, *y* and *z* directions at the boundaries. The mechanical behaviour of each geogrid can be divided into the structural response of the geogrid material itself and the way in which the geogrid interacts with the FLAC grid. By default, plane-stress elements, which resist membrane but do not resist bending loads, are assigned to the geogrids. A membrane structure can be modelled as a collection of the geogrids. The geogrid behaves as an isotropic or orthotropic, linear elastic material with no failure limit. A shear-directed (in the tangent plane to the geogrid surface) frictional interaction occurs between the geogrid and the FLAC3D grid, and the geogrid is slaved to the grid motion in the normal direction. The geogrid can be thought of as a two-dimensional analogue of the one-dimensional cable. Geogrids are used to model the flexible membranes, whose shear interactions with the soils are important, such as geo-textiles and geogrids (Itasca FLAC 3D ver.5 manuals 2012).

The grid- anchors modelled as a cable element are one of the FLAC structural elements. Each cable structural element is defined by its geometric, material and grout properties. A cable is assumed to be a straight segment of uniform cross-sectional and material properties lying between the two nodal points. An arbitrarily curved structural cable can be modelled as a curvilinear structure composed of a collection of cables. The cable behaves as an elastic, perfectly plastic material that can yield in tension, although it cannot resist a bending moment. A cable may be grouted such that force develops along its length in response to relative motion between the cable and the grid. The grout behaves as an elastic, perfectly plastic material, with its peak strength being dependent on the stress, and with no loss of strength after failure. Cables are suitable for modeling the structural-support members in which tensile capacity is important, and in which the axially directed frictional interaction with the rock or soil mass occurs. Each cable has its own local coordinate system, as shown in Fig. 2. This system is used to define the average axial anchor direction. The anchor coordinate system is defined by the locations of its two nodal points, labeled as 1 and 2. Fig. 3 shows the idealization of the grid-anchor system (Itasca FLAC 3D ver.5 manuals 2012).

Primary models testified that if the width of model chooses more than 8D (where D is pipe

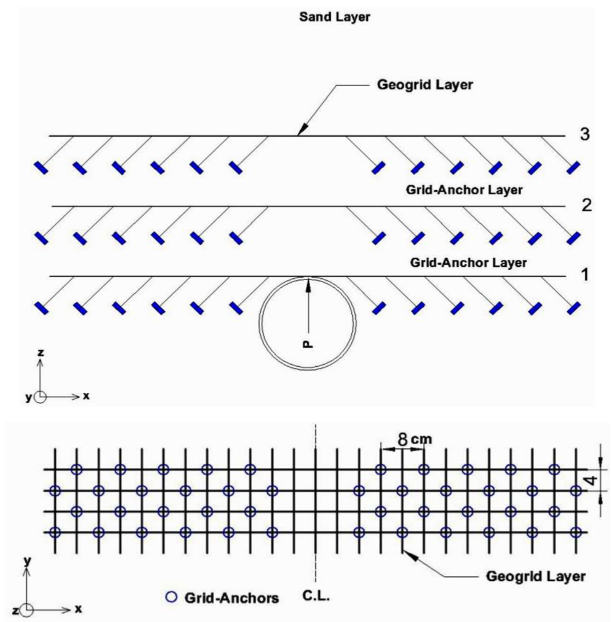


Fig. 2 Schematic arrangement of the grid-anchor system

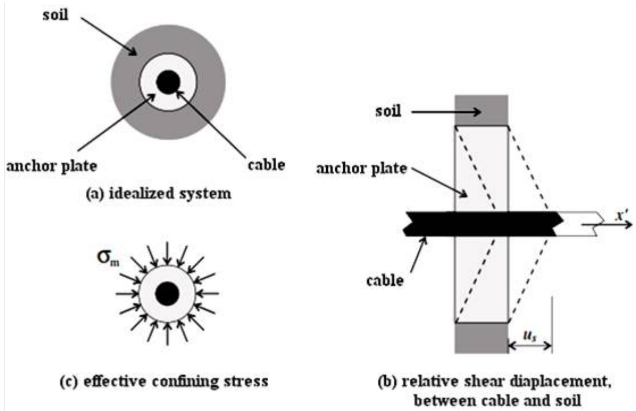


Fig. 3 Idealization of grid-anchor system (FLAC 3D ver.5 manuals 2012)

Table 1 Parameters used in the analysis

Parameter	value
Soil angle of internal friction	31° and 40°
Soil cohesion (kPa)	0
Soil modulus of elasticity (kPa)	8000 and 12000
Poisson's ratio	0.3
Soil unit weight (kN/m^3)	13.5 and 18
Soil type	sand
Soil constitutive model	Mohr–Coulomb
Axial stiffness of geogrids (kN/m)	28
Axial stiffness of anchors (kN)	0.08
Pipe diameter (mm)	50, 100 and 200
Length of anchors (mm)	80
Anchor plates diameter (mm)	30
Horizontal angel of anchors	45°

diameter), boundary conditions effects would be negligible. So for avoiding boundary effects, 8D in width was used in the models. The results show that the displacement has not reached the boundaries in the analysis. Also dimensions with 100 cm in length and 5D (because the pipe maximum burial depth, the pipe diameter and soil height under the pipe are 3D, D and D respectively) in height have selected. A total of 26 pullout models were conducted to determine the uplift resistance of the buried pipes and the failure mechanism involved. Sand was reinforced by geogrid and grid-anchor system with a width of 3D, 5D and 8D in models. In some models, no reinforcing system was used.

The finite difference mesh employed for the analysis is shown in Fig. 4 and arrangement of the reinforcement layers for the pre-uplift and post-uplift states are shown in Figs. 5(a)-(b).

The pipe with a length of 100 cm was simply buried in sand with an embedment ratio (h/D) of 1, 2 and 3. The pipes were pulled out from the soil using an uplift force. In order to model the pullout

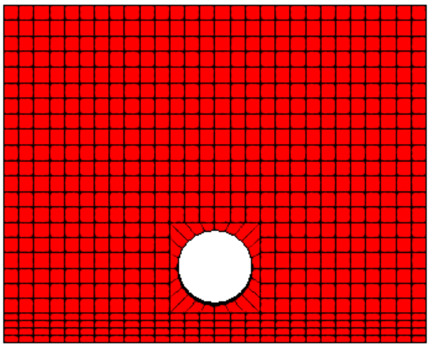
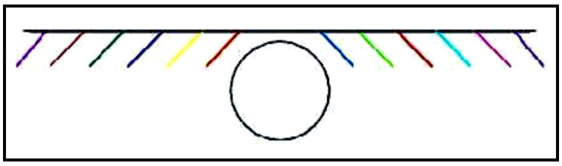


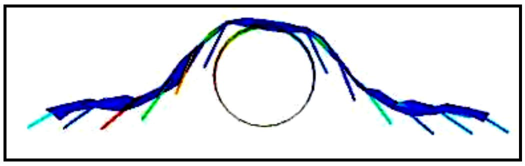
Fig. 4 3D mesh at section plane across the model center

Table 2 Summary parameters for models and results

Model reference number	Pipe diameter, D (mm)	Embedment ratio (*h*/*D*)	Reinforcement system	Width of Rein. layer, *b* (mm)	Number of Rein. layers, *N*	Soil unit weight, γ (kN/m^3)	peak uplift resistance, PUR (N)
M_1	50	3	non-reinforced	---	---	13.5	325
M_2	50	3	geogrid	5D	1	13.5	425
M_3	50	3	grid-anchor	5D	1	13.5	657
M_4	50	2	non-reinforced	---	---	13.5	175
M_5	50	2	geogrid	5D	1	13.5	242
M_6	50	2	grid-anchor	5D	1	13.5	507
M_7	50	1	non-reinforced	---	---	13.5	75
M_8	50	1	geogrid	5D	1	13.5	110
M_9	50	1	grid-anchor	5D	1	13.5	240
M_{10}	50	2	geogrid	3D	1	13.5	192
M_{11}	50	2	grid-anchor	3D	1	13.5	350
M_{12}	50	2	geogrid	8D	1	13.5	271
M_{13}	50	2	grid-anchor	8D	1	13.5	650
M_{14}	100	2	geogrid	5D	2	13.5	900
M_{15}	100	2	grid-anchor	5D	2	13.5	1175
M_{16}	100	2	geogrid	5D	3	13.5	925
M_{17}	100	2	grid-anchor	5D	3	13.5	1187
M_{18}	50	3	non-reinforced	---	---	18	450
M_{19}	50	3	geogrid	5D	1	18	520
M_{20}	50	3	grid-anchor	5D	1	18	807
M_{21}	100	2	non-reinforced	---	---	13.5	700
M_{22}	100	2	geogrid	5D	1	13.5	875
M_{23}	100	2	grid-anchor	5D	1	13.5	1125
M_{24}	200	2	non-reinforced	---	---	13.5	3125
M_{25}	200	2	geogrid	5D	1	13.5	3375
M_{26}	200	2	grid-anchor	5D	1	13.5	4450



(a) Undeformed elements before pipe uplift



(b) Deformed elements after pipe uplift

Fig. 5 Pipe, geogrid and grid-anchors arrangement for a 1 layer of reinforcement model

Table 3 Prediction models for peak uplift resistance (Cheuk *et al*. 2008)

Reference	Prediction model	Assumed mechanism
Schaminée *et al*. (1990)	$P = \gamma' HD + \gamma' H^2 K \tan \varphi$	Vertical slip surfaces
Ng and Springman (1994)	$P = \gamma' HD + \gamma' H^2 K \tan \varphi_{\max}$	Sliding block with inclined failure surfaces
Vermeer and Sutjiadi (1985)	$P = \gamma' HD + \gamma' H^2 K \tan \varphi_{\max} \cos\varphi_{crit}$	Sliding block with inclined failure surfaces
White *et al*. (2001)	$P = \gamma' HD + \gamma' H^2 K \tan \varphi$ $+ \gamma' H^2 K(\tan \varphi_{\max} - \tan\varphi)[(1 + K_0)\cos 2\varphi/2]$	Sliding block with inclined failure surfaces

force, a point load was applied on top of the pipe section. The burial materials consisted of standard sand at two different unit weights (13.5 and 18 kN/m3). The model parameters and peak uplift resistance are summarized in Table 2.

4. Finite difference model validation

A convenient way to examine the validity of a model is to compare the model results with the recent results out of the other researchers' studies. For non-reinforced pipeline, various models have been proposed for the calculation of peak uplift resistance based on the mechanisms observed in previous model tests. Key prediction methods and the underlying assumptions are listed in Table 3. All methods assume that tension cannot be sustained between the pipe invert and the soil, allowing a gap to open without resistance (Cheuk *et al*. 2008).

In this paper, the comparison of modeling outcomes with the prediction models listed in Table 3, demonstrated a very good agreement. For instance, according to the proposed model by White *et al*. (2001), peak uplift resistance per unit length of the pipe with a diameter of 50 mm and an embedment ratio (h/D) of 3 buried in loose sand will be 320 N; In this study, however, its value is 325 N. Furthermore, for a pipe with a diameter of 55 mm and an embedment ratio of 3, buried in loose sand reinforced with a geogrid layer of width 300 mm, the peak uplift resistance was approximately 550 N, according to Faizi *et al*. (2014). In this research, though, for a pipe with a diameter of 50 mm and an embedment ratio of 3, buried in loose sand reinforced with a geogrid layer of width 250 mm, this value is 425 N. This negligible difference is due to the diameter and burial depth differences. Thus, the comparison reveals that the results of the finite difference analysis here generally are in good accordance with the experimental and numerical results of the most recent studies.

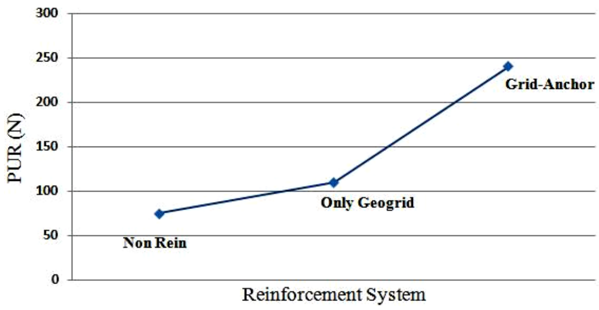


Fig. 6 Variation of peak uplift resistance (PUR) with selected reinforcing system (D = 50 mm, N = 1, h/D = 1, b = 250 mm)

5. Verification of effectiveness of the grid-anchor system

In order to verify the efficiency of the grid–anchor system in improving the uplift capacity of pipelines, the behavior of the pipelines buried in non-reinforced sand, sand reinforced with ordinary geogrid and sand reinforced with grid–anchor system under the same conditions (soil properties, N, b/D, h/D, anchor and reinforcement stiffness) were investigated. Fig. 6 shows the comparison between these three statuses. The effectiveness of using grid-anchor system as reinforcement elements in increasing the uplift capacity of pipelines is evident. As it can be noticed, the value of peak uplift resistance (PUR) is roughly three times greater than that for non-reinforced sand and two times greater than that for ordinary geogrid in this case. Fig. 7 shows the uplift force versus the pipe vertical displacement diagram for three statuses. The diagram accentuates employing the geogrid and grid-anchor system to enhance the uplift resistance.

For the models M_7, M_8 and M_9 conducted at soil density of 1350 kg/m^3, reinforcing width of 5D (b = 250 mm) and burial depth of 1D (h = 50 mm), the measured peak uplift resistance (PUR) was 75,110 and 240 N, respectively. Overall, the results in Fig. 6 suggest the efficiency of using grid–anchor system to enhance the uplift resistance of buried pipelines. As expected, the use of geogrid and grid–anchor system to reinforcing the burial soil of the pipe resulted in higher uplift resistance and a ductile-like post-peak behaviour. As illustrated in Fig. 6, in loose soils, the uplift resistance in the model using geogrid and in the model using grid-anchor was approximately 47% and 320% higher than the value in the non-reinforced soils, respectively.

6. Overview of soil failure mechanism studies

Research on the uplift failure mechanism has revealed that the buried pipelines would fail with a curved shear surface, as shown in Figs. 8-10. The shear failure mechanism during uplift for buried pipelines in non-reinforced, reinforced with ordinary geogrid, and reinforced with grid–anchor system under the same conditions is illustrated in Figs. 8-10. A contributing factor towards the formation of the curved shaped failure would be the collapse of the soil around the pipe to fill in the void space formed near the bottom of the pipe. Figs. 8-10 illustrate different buried pipelines' deflection behaviour during uplift for buried pipelines in non-reinforced, reinforced with ordinary geogrid, and reinforced with grid–anchor system in loose sand. Figs. 8-10 also indicate the formation of a shear zone during uplift. This mechanism is illustrated by

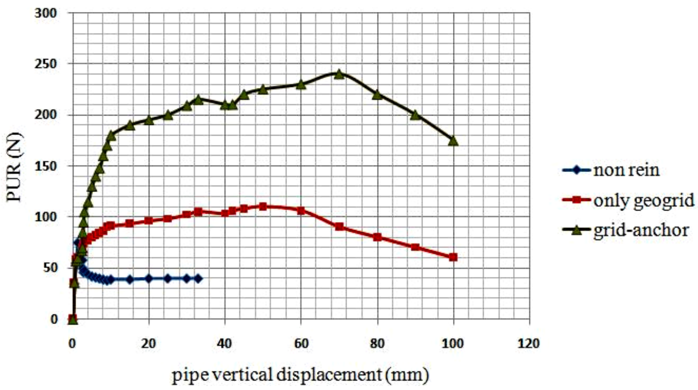


Fig. 7 Uplift force versus pipe vertical displacement curves for models M_7, M_8 and M_9 (D = 50 mm, N = 1, h/D = 1, b = 250 mm)

movement of the soil particles along the pipeline-soil interface, which follow the pipeline during uplift. This shear zone comprises displaced soil particles along the pipeline-soil interface, therefore it is considered to be influential in increasing the uplift capacity. The outfitted tension trend in the reinforcement allows the geogrid and grid–anchor to resist the formed horizontal shear stresses built up in the sand mass, inside the loaded zone, and moves them beside the stable layers of sand, which leads to a broader and deeper failure zone.

7. Parametric studies

The discussion of uplift capacity of the pipelines in reinforced sand involves a separate analysis of the parameters including the number of reinforcement layers, width of reinforcement layers, stiffness of reinforcement layers, embedment ratio of the pipeline, soil density, and pipe diameter. Geogrid as a type of the geosynthetics and grid–anchor systems is used in this study. In order to determine the effect of different factors on the uplift capacity of sand reinforced with the geogrid and grid–anchor system, an analysis has been performed and the outcomes are presented as follows.

7.1 Influence of pipe's embedment ratio (h/D) on the uplift capacity in dry sand

Regarding Fig. 11, pipelines experienced an increase in the uplift capacity for every increase of the embedment ratio. Analysis of this model series is in correlation with the model series M_1, M_2, M_3, M_4, M_5, M_6, M_7, M_8 and M_9. In these models, a pipe with a diameter of 50 mm is conducted at the soil density of 1350 kg/m^3, reinforcing width of 5D (b = 250 mm) and burial depth of 1D-3D (h = 50-150 mm).

The measured peak uplift resistance (PUR) of pipelines buried in non-reinforced soil were 325, 175 and 75 N at h/D = 3, 2 and 1, respectively. As seen from Fig. 11, compared to the pipelines with minimum embedment ratio, h/D =1, pipelines with maximum embedment ratio, h/D = 3, had higher uplift capacities. This is similar to the results by Saboya *et al*. (2012) and Wang *et al*. (2012) who demonstrated significant differences in the uplift capacity values between various embedment ratios.

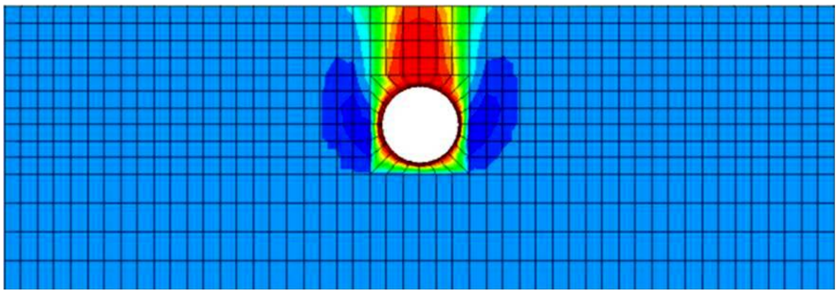


Fig. 8 State of sand after commencement of uplift in non-reinforced loose sand

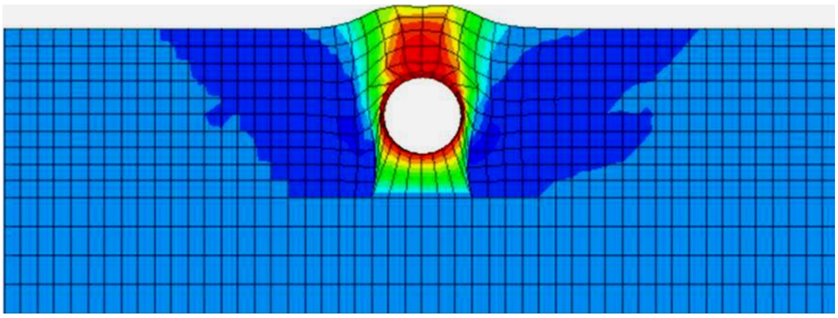


Fig. 9 State of sand after commencement of uplift in geogrid-reinforced loose sand

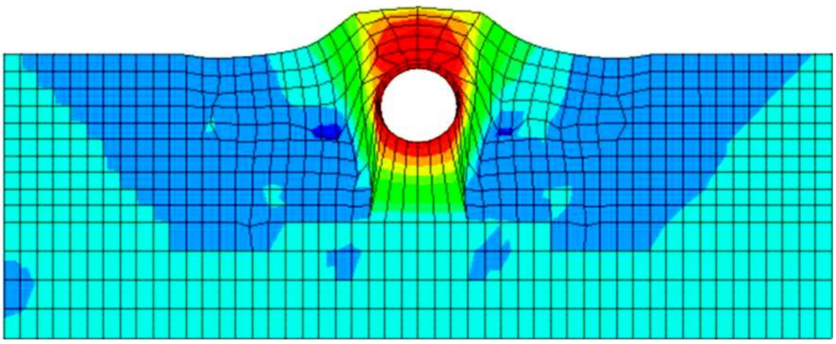


Fig. 10 State of sand after commencement of uplift in grid–anchor reinforced loose sand

The measured peak uplift resistance (PUR) of pipelines buried in sand and reinforced with geogrid was 425, 275 and 110 N at $h/D = 3$, 2 and 1. This is similar to the findings of Saboya *et al*. (2012) and Faizi *et al*. (2014).

The measured peak uplift resistance (PUR) of pipelines buried in the sand reinforced with grid–anchor system was 657, 507 and 240 N for $h/D = 3$, 2 and 1, respectively. In the case of loose sands reinforced with grid–anchor, these findings show that the increase in the uplift resistance in models with an embedment ratio of 1 was approximately 320%, in model with an embedment ratio of 2 was roughly 290%, and in model with an embedment ratio of 3 was approximately 200%. Therefore, the efficiency of the grid–anchor system in lower embedment ratios is more than that of the higher embedment ratios.

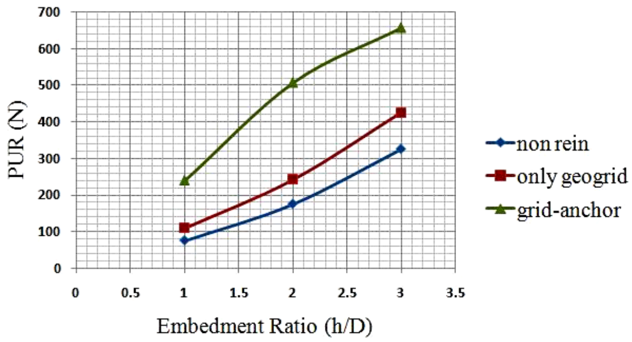


Fig. 11 Variation of PUR with embedment ratio (*h*/*D*) for buried pipelines in loose sand

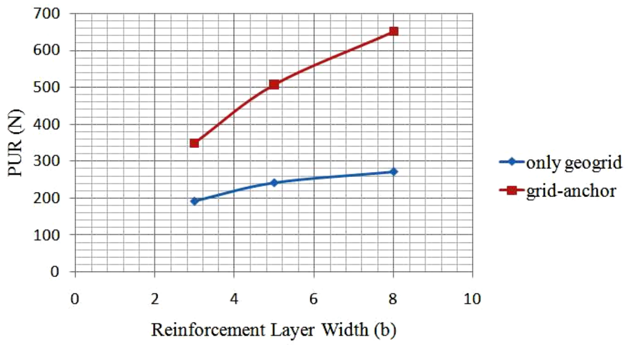


Fig. 12 Variation of PUR with reinforcement width (b) for pipelines in loose dry sand

7.2 Influence of reinforcement layer width on the uplift capacity in dry sand

Numerical studies have demonstrated that the PUR is generally increased with a growth in the reinforcement width (b). The uplift capacity obtained from these analyses has been plotted with b (3D, 5D and 8D) in Fig. 12. Analysis of these model series is in correlation with the model series M_5, M_6, M_{10}, M_{11}, M_{12}, and M_{13}. In these models, a pipe with a diameter of 50 mm is conducted at soil density of 1350 kg/m^3, reinforcement width of 3D, 5D and 8D (b = 150, 250 and 400 mm) and burial depth of 2D (h =100 mm).

Values of the measured peak uplift resistance (PUR) of pipelines buried in sand reinforced with geogrid were 192, 242 and 272 N for h/D = 2. This is similar to the findings of Faizi *et al*. (2014).

Fig. 12 also indicates that the increasing reinforcement width beyond a certain value would not increase the PUR significantly. For the pipelines, the optimum ratio of b/D was approximately equal to 5. As it can be noticed, the PUR increased rapidly as the reinforcing size increased from 3 to 5 times the pipes’ diameter.

For the pipelines buried in sand reinforced with grid–anchor system, PURs were 350, 507 and 650 N for h/D = 2. This means that an increasing reinforcement width will considerably increase the PUR.

7.3 Influence of reinforcement layers number (N)

Numerical analysis indicated that the value of PUR doesn’t change drastically with the number of reinforcement layers, *N*. Analyses were performed on six models (M_6, M_7, M_{14}, M_{15}, M_{16} and M_{17}) to study the effect of reinforced sand with various number of geogrid and grid–anchor inclusions on the behavior of the pipeline with a diameter of 100 mm, located at the loose sand and at an embedment ratio of 2 (h = 200 mm). In reinforced models, reinforcement layers were placed at an equal vertical spacing of 70 mm with the first layer resting on the pipe. The variations of pipeline's capacities with various number of reinforcement layers are plotted in Fig. 13. With regard to Fig. 13, it is clear that the number of reinforcement layers has no significant effect on the pipe uplift resistance. In fact, inclusion of one reinforcement layer resting directly on top of the pipe has the same effect as the inclusion of multi-layers, approximately. Thus, in terms of the pipeline's capacity, it was concluded that employing one reinforcement layer is better and more economical than reinforcing the soil with several layers. The reason is that both conditions have the same failure zone angle (Niroumand *et al.* 2013). This is similar to Faizi *et al.* (2014) for pipelines, Niroumand *et al.* (2013) for plate anchors, and Ghosh and Bera (2010) for anchors, who indicated that the number of reinforcement layers does not have a significant effect on the uplift resistance.

7.4 Influence of sand unit weight on the pipeline uplift capacity

For the models M_1, M_2 and M_3, sand unit weight and burial depth were equal to 13.5 kN/m^3 and 3D, respectively. For these models, the peak uplift resistance (PUR) reached the values of 325, 425 and 657 N, respectively. For the models M_{18}, M_{19} and M_{20} conducted at sand unit weight of 18 kN/m^3 and burial depth of 3D, the measured peak uplift resistance (PUR) was 450, 520 and 807 N, respectively. As expected, the use of compact soil resulted in higher uplift resistance.

In dense soils, for the models with non-reinforcement layer, with a geogrid width of 5D, and with a grid-anchor system, the values of uplift resistance were roughly 34%, 16%, and 23% higher than those in loose sands. As shown in Fig. 14, in loose soils, the values of uplift resistance in models utilizing the geogrid was approximately 30%, and in models utilizing the grid–anchor was approximately 202% higher than those in non-reinforced soil. These values were approximately equal to 15% and 79% of values in dense soils. This means that the efficiency of including the reinforcement layer for uplift resistance in loose sand is higher than in dense sand, despite the fact that the amount of uplift resistance is higher in dense sands. This is similar to the findings by Saboya *et al.* (2012).

7.5 Influence of pipe diameter on the pipeline uplift capacity

For the models M_4, M_5, M_6, M_{21}, M_{22}, M_{23}, M_{24}, M_{25} and M_{26} conducted at sand unit weight of 13.5 kN/m^3, reinforcement width of 5D, and the burial depth of 2D, values of the measured peak uplift resistance (PUR) were as Fig. 15.

With reference to Fig. 15, for every increase in the pipeline diameter, pipelines experienced an increase in the uplift capacity. This growth, however, was non-linear. Fig. 15 illustrates pipelines exhibiting non-linear increases for the uplift capacity in pipe diameter when placed in sand with loose packing.

The Fig. 15 shows that the efficiency of reinforcement layer inclusion for increasing the uplift resistance of pipelines decreases with a growth in diameter. Therefore, compared to non-reinforced soils, for the pipes with a diameter of 50 mm, values of the uplift resistance for the models with geogrid, and for the models with grid-anchor were 38% and 289% higher, respectively. But for the pipe with 100 mm diameter these values were approximately 25% and 61%, and for the pipe with 200 mm diameter these values were approximately 8% and 42%. This means that by increasing the pipe diameter, the efficiency of reinforcement layer inclusion will be lower. Therefore, the

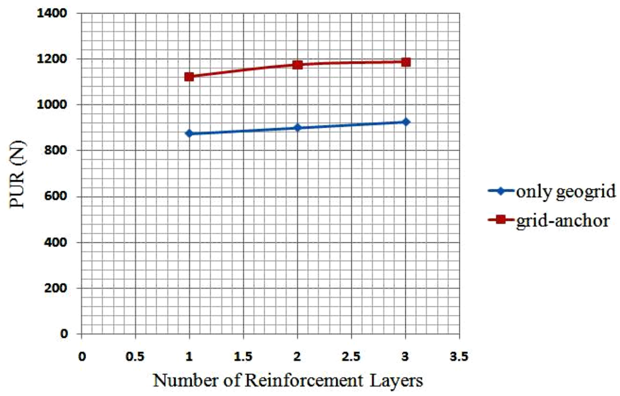


Fig. 13 Variation of PUR with various number of reinforcement layers (N) for pipelines in loose sand

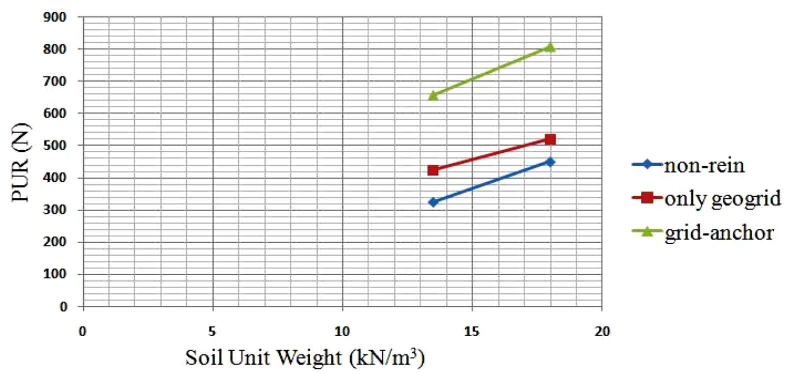


Fig. 14 Variation of PUR with soil unit weight for pipelines in loose and dense sand

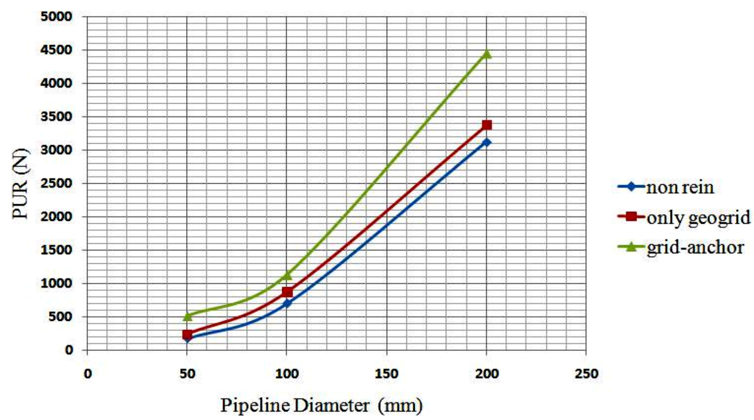


Fig. 15 Variation of PUR with pipeline diameter in loose sand

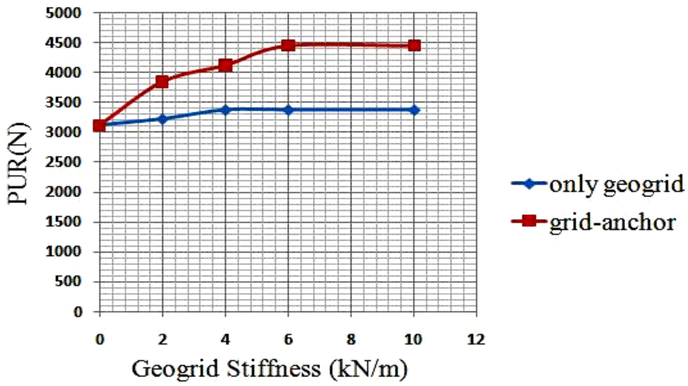


Fig. 16 Variation of PUR with geogrid stiffness (D = 200 mm, N = 1, h/D = 2, b = 5D)

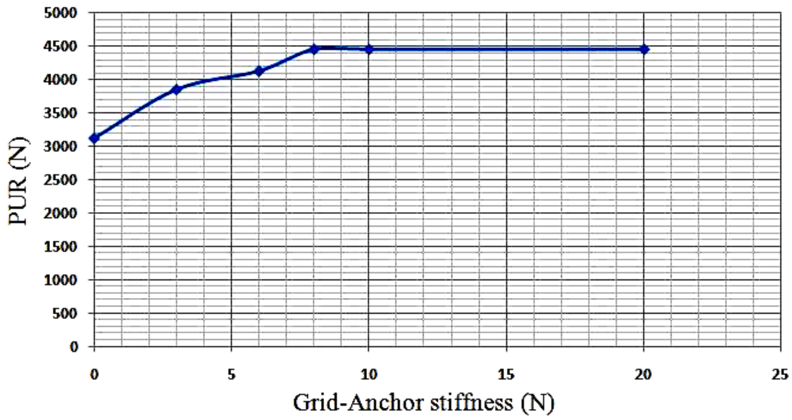


Fig. 17 Variation of PUR with grid-anchor stiffness (D = 200 mm, N = 1, h/D = 2, b = 5D)

application of reinforcement layers will be economical and effective for small diameter pipelines, only.

7.6 Influence of geogrid and anchors stiffness on the pipeline uplift capacity

In the analysis, geogrid stiffness, "EA" varied from 1 kN/m to 100 kN/m. Typical variation of PUR with the geogrid stiffness for one layer reinforcement is shown in Fig. 16. It can be perceived that increasing the reinforcement stiffness beyond an axial stiffness of approximately 6 kN/m would not result in a significant increase in the PUR for a single layer reinforcement. The reason for this phenomenon is that before the axial stiffness of the reinforcement is fully mobilized, geogrid is pulled out and the soil body will slide over the reinforcement. Therefore, application of high stiffness geogrid is not necessary for increasing the uplift capacity of pipelines.

The fixed-end anchor which is a two-node cable element with a constant stiffness tied to a single point of geogrid layer was employed to model the anchorage system. In the analysis, the axial force of the anchors varied from 0.0 N to 8 N. Therefore, like the geogrid, application of high stiffness anchors is not necessary for increasing the uplift capacity of pipelines. Fig. 17 shows a typical variation of PUR with the anchor stiffness for single layer reinforcement.

8. Conclusions

A three dimensional finite difference parametric research was conducted to investigate the uplift capacity of buried pipelines. In this study, a new anchoring system using geogrid and innovative grid-anchor as a reinforcement element is proposed to improve geogrid efficiency. This new system improves the uplift resistance and inhibits the upward movement of pipes. Compared to using the ordinary geogrid, the application of innovative grid-anchor as a reinforcement element for improving the uplift capacity of soils was investigated and it was shown that a significant increase in the uplift capacity was obtained. The effects of the number of reinforcement layers, width of reinforcement layer, embedment ratio of pipeline, soil density, pipe diameter, and stiffness of geogrids and anchors on the uplift capacity were also investigated. The study brings the following conclusions:

- Grid-anchor system of reinforcing can increase the uplift capacity 2.18 times greater than that for an ordinary geogrid and 3.20 times greater than that for the non-reinforced sand.
- Due to a developed longer failure surface, inclusion of grid-anchor system in the soil deposit significantly increases the uplift capacity.
- In cases where design requirements necessitate large uplift resistance, soil reinforcement can be considered as an economical solution, and it can be used to obtain the design capacity of the pipeline instead of increasing the embedment depth.
- In terms of pipeline uplift capacity, inclusion of one layer of reinforcement over the pipeline is more cost effective than sand reinforcement using multiple layers. The optimal location of one reinforcement inclusion is where it is resting directly on top of the pipeline.
- Increased soil density results in a greater uplift capacity. But the efficiency of reinforcement layer inclusion for uplift resistance in loose sand is higher than in dense sand; the amount of the uplift resistance in dense sand is higher, though.
- Increased pipeline embedment ratio results in a greater uplift capacity. But the efficiency of reinforcement layer inclusion for the uplift resistance in lower embedment ratios is greater than the higher embedment ratios; however, the amount of the uplift resistance in greater embedment ratios is higher.
- For the pipelines buried in sand reinforced with grid-anchor system, increasing reinforcement width will increase the uplift resistance significantly.
- By increasing the pipe diameter, the efficiency of the reinforcement layer inclusion will be lower. That is, inclusion of reinforcement layers will be more economical and effective only for small diameter pipelines.
- The application of high stiffness geogrids and grid-anchors is not required for increasing the uplift capacity of pipelines.

Since the experimental studies on the uplift resistance of the buried pipelines reinforced with grid-anchor system have not been investigated, to establish a more accurate design criteria for grid-anchor reinforcing system, further experimental studies are in progress by the authors.

References

Bransby, M.F., Newson, T.A., Davies, M.C.R. and Brunning, P. (2002), “Physical modeling of the upheaval resistance of buried offshore pipelines”, *Proceedings of the 4th International Conference on Physical*

Modeling in Geomechanics, St. Johns, NY, USA, July, pp. 899-904.
Cheuk, C.Y., White, D.J. and Bolton, M.D. (2005), "Deformation mechanisms during the uplift of buried pipelines in sand", *Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, Japan, September, pp. 1685-1688.
Cheuk, C.Y., White, D.J. and Bolton, M.D. (2008), "Uplift mechanics of pipes buried in sand", *J. Geotech. Geoenviron. Eng.*, **134**(2), 154-163.
Choobbasti, A.V., Vahdatirad, M., Firouzian Bandpey, S., Barari, A. and Rezaei, D. (2009), "Modeling of the uplift response of buried pipelines", *Electron. J. Geotech. Eng.*, **14**, 001-015.
Dikin, E.A. (1994), "Uplift resistance of buried pipelines in sand", *J. Soil. Found.*, **34**(2), 41-48.
Faizi, K., Jahed Armaghani, D., Momeni, E., Nazir, R. and Tonnizam Mohamad, E. (2014), "Uplift resistance of buried pipelines enhanced by geogrid", *Soil Mech. Found. Eng.*, **51**(4), 188-195.
Finch, M. (1999), "Upheaval buckling and floatation of rigid pipelines: the influence of recent geotechnical research on the current state of the art", *Offshore Technology Conference*, Houston, TX, USA, May.
Ghosh, A. and Bera, A.K. (2010), "Effect of geotextile ties on uplift capacity of anchors embedded in sand", *J. Geotech. Geoenviron. Eng.*, **28**(5), 567-577.
Hataf, N., Boushehrian, A.H. and Ghahramani, A. (2010), "Experimental and numerical behavior of shallow foundations on sand reinforced with geogrid and grid-anchor under cyclic loading", *Scientia Iranica. Transaction A*, *Civil Engineering*, **17**(1), 1-10.
Huang, B., Liu, J., Lin, P. and Ling, D. (2014), "Uplifting behavior of shallow buried pipe in liquefiable soil by dynamic centrifuge test", *The Scientific World Journal*, Article ID 838546.
Itasca (2012), FLAC-3D Version 5.0, Itasca Consulting Group, Inc., Minneapolis, MN, USA.
Jahed Armaghani, D., Faizi, K., Hajihassani, M., Tonnizam Mohamad, E. and Nazir, R. (2015), "Effects of soil reinforcement on uplift resistance of buried pipeline", *J. Measure.*, **64**, 57-63.
Keskin, M.S. (2015), "Model studies of uplift capacity behavior of square plate anchors in geogrid-reinforced sand", *Geomech. Eng.*, *Int. J.*, **8**(4), 595-613.
Lee, H. (2010), "Finite element analysis of a buried pipeline", Master's Thesis; University of Manchester, Manchester, UK.
Mohri, Y., Kawabata, T. and Fujita, N. (2001), "Large-scale experiment on shallow cover for buried pipeline reinforced with geosynthetics", *J. Pipeline Syst. Eng. Pract.*, **52**, 1-13.
Mosallanezhad, M., Hataf, N. and Ghahramani, A. (2007), "Experimental study of bearing capacity of granular soils, reinforced with innovative grid-anchor system", *J. Geotech. Geol. Eng.*, **25**(1), 123-137.
Mosallanezhad, M., Hataf, N. and Ghahramani, A. (2010), "Three dimensional bearing capacity analyses of granular soils, reinforced with innovative grid-anchor system", *Iran. J. Sci. Technol.*, *Transaction B*: *Eng.*, **34**(4), 419-431.
Newson, T.A. and Deljoui, P. (2006), "Finite element modeling of upheaval buckling of buried offshore pipelines in clayey soils", *Soil Rock Behavior Model.*, 351-358.
Niroumand, H. and Kassim, K.A. (2013), "A review on uplift response of symmetrical anchor plates embedded in reinforced sand", *Geomech. Eng.*, *Int. J.*, **5**(3), 187-194.
Niroumand, H. and Kassim, K.A. (2014a), "Uplift response of circular plates as symmetrical anchor plates in loose sand", *Geomech. Eng.*, *Int. J.*, **6**(4), 321-340.
Niroumand, H. and Kassim, K.A. (2014b), "Experimental and numerical modeling of uplift behavior of rectangular plates in cohesionless soil", *Geomech. Eng.*, *Int. J.*, **6**(4), 341-358.
Niroumand, H. and Kassim, K.A. (2014c), "Square plates as symmetrical anchor plates under uplift test in loose sand", *Geomech. Eng.*, *Int. J.*, **6**(6), 593-612.
Niroumand, H., Kassim, K.A. and Nazir, R. (2013), "The influence of soil reinforcement on the uplift response of symmetrical anchor plate embedded in sand", *J. Measure.*, **46**(8), 2608-2629.
Robert, D. and Thusyanthan, N. (2015), "Numerical and experimental study of uplift mobilization of buried pipelines in sands", *J. Pipeline Syst. Eng. Pract.*, **6**(1), CID:04014009.
Rowe, R.K. and Davis, E.H. (1982), "The behaviour of anchor plates in sand", *Geotechnique*, **32**(1), 025-041.
Saboya, F.A., Santiago, P.C., Martins, R.R., Tibana, S., Ramires, R.S. and Araruna, J.T. (2012), "Centrifuge

test to evaluate the geotechnical performance of anchored buried pipelines in sand", *J. Pipeline Syst. Eng. Pract.*, **3**(3), 84-97.

Selvadurai, A.P.S. (1989), "The enhancement of the uplift capacity of buried pipelines by the use of geogrids", *J. Geotech. Geoenviron. Eng.*, **124**(8), 211-216.

Thusyanthan, N.I., Ganesan, S.A. Bolton, M.D. and Allan, P. (2008), "Upheaval buckling resistance of pipelines buried in clayey backfill", *Proceedings of the 18th International Offshore and Polar Engineering Conference*, Vancouver, BC, Canada, July, pp. 6-11.

Trautmann, C.H., O'Rourke, T.D. and Kulhawy, F.H. (1985), "Uplift force-displacement response of buried pipe", *J. Geotech. Eng.*, **111**(9), 1061-1076.

Wang, J., Haigh, S.K., Forrest, G. and Thusyanthan, N.I. (2012), "Mobilization distance for upheaval buckling of shallowly buried pipelines", *J. Pipeline Syst. Eng. Pract.*, **3**(4), 106-114.

White, D.J., Barefoot, A.J. and Bolton, M.D. (2001), "Centrifuge modeling of upheaval buckling in sand", *Int. J. Phys. Model. Geotech.*, **1**(2), 019-028.

White, D.J., Cheuk, C.Y. and Bolton, M.D. (2008), "The uplift resistance of pipes and plate anchors buried in sand", *Geotechnique*, **58**(10), 771-779.

Zhu, H.H., Mei, G.X., Xu, M., Liu, Y. and Yin, J.H. (2014), "Experimental and numerical investigation of uplift behavior of umbrella-shaped ground anchor", *Geomech. Eng.*, *Int. J.*, **7**(2), 165-181.

CC